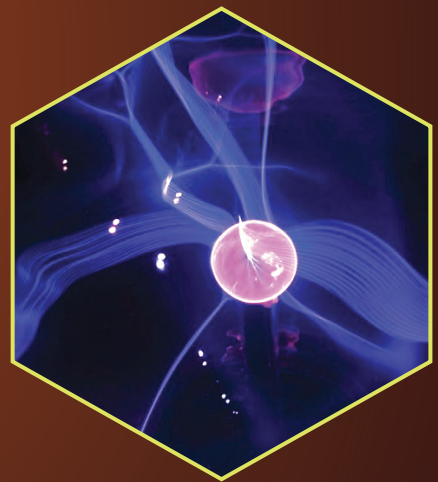
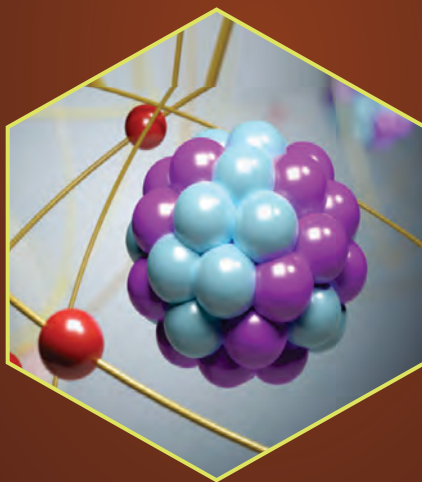
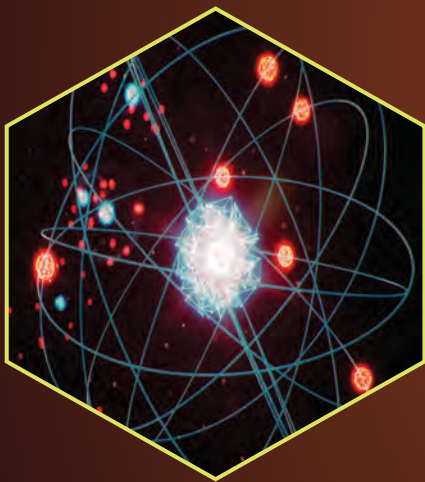


NEW AGE

THIRD EDITION

NUCLEAR PHYSICS

THEORY AND EXPERIMENT



R R ROY • B P NIGAM



NEW AGE INTERNATIONAL PUBLISHERS

NUCLEAR PHYSICS

THEORY AND EXPERIMENT

THIRD EDITION

R R ROY

Former Professor
Department of Physics
Arizona State University, USA

B P NIGAM

Former Professor
Department of Physics
Arizona State University, USA

Committed to Educate the Nation



Publishing Globally

IN INDIA

NEW AGE INTERNATIONAL (P) LIMITED, PUBLISHERS

LONDON • NEW DELHI

Bangalore • Chennai • Cochin • Guwahati • Hyderabad • Kolkata • Mumbai

Visit us at www.newagepublishers.com

Copyright © 2023, 2014, 1967, New Age International (P) Ltd., Publishers

Published by New Age International (P) Ltd., Publishers

First Edition: 1967

Third Edition: 2023

All rights reserved.

No part of this book may be reproduced in any form, by photostat, microfilm, xerography, or any other means, or incorporated into any information retrieval system, electronic or mechanical, without the written permission of the publisher.

GLOBAL OFFICES

- **New Delhi** **NEW AGE INTERNATIONAL (P) LIMITED, PUBLISHERS**
7/30 A, Daryaganj, New Delhi-110002, (INDIA), **Tel.:** (011) 23253472, 23253771, **Mob.:** 9315905300
E-mail: contactus@newagepublishers.com • Visit us at www.newagepublishers.com
- **London** **NEW AGE INTERNATIONAL (UK) LTD.**
27 Old Gloucester Street, London, WC1N 3AX, UK
E-mail: info@newacademicscience.co.uk • Visit us at www.newacademicscience.co.uk

BRANCHES

- **Bangalore** 37/10, 8th Cross (Near Hanuman Temple), Azad Nagar, Chamarajpet, Bangalore- 560 018
Tel.: (080) 26756823, **Mob.:** 9315905288, **E-mail:** bangalore@newagepublishers.com
- **Chennai** 26, Damodaran Street, T. Nagar, Chennai-600 017, **Tel.:** (044) 24353401, **Mob.:** 9315905309
E-mail: chennai@newagepublishers.com
- **Cochin** CC-39/1016, Carrier Station Road, Ernakulam South, Cochin-682 016
Tel.: (0484) 4051304, **Mob.:** 9315905289, **E-mail:** cochin@newagepublishers.com
- **Guwahati** Hemsan Complex, Mohd. Shah Road, Paltan Bazar, Near Starline Hotel
Guwahati-781 008, **Tel.:** (0361) 2513881, **Mob.:** 9315905296
E-mail: guwahati@newagepublishers.com
- **Hyderabad** 105, 1st Floor, Madhiray Kaveri Tower, 3-2-19, Azam Jahi Road, Near Kumar Theater
Nimboliadda Kachiguda, Hyderabad-500 027, **Tel.:** (040) 24652456, **Mob.:** 9315905326
E-mail: hyderabad@newagepublishers.com
- **Kolkata** RDB Chambers (Formerly Lotus Cinema) 106A, 1st Floor, S N Banerjee Road
Kolkata-700 014, **Tel.:** (033) 22273773, **Mob.:** 9315905319
E-mail: kolkata@newagepublishers.com
- **Mumbai** 142C, Victor House, Ground Floor, N.M. Joshi Marg, Lower Parel, Mumbai-400 013
Tel.: (022) 24927869, 24915415, **Mob.:** 9315905282, **E-mail:** mumbai@newagepublishers.com
- **New Delhi** 22, Golden House, Daryaganj, New Delhi-110 002, **Tel.:** (011) 23262368, 23262370
Mob.: 9315905300, **E-mail:** sales@newagepublishers.com

C-22-08-13276

Printed in India at Ajit Printing Press, Delhi.

Typeset at Inhouse + Aakriti Graphics, Delhi.

NEW AGE INTERNATIONAL (P) LIMITED, PUBLISHERS

7/30 A, Daryaganj, New Delhi - 110002

Visit us at www.newagepublishers.com

(CIN: U74899DL1966PTC004618)

 [Click Here to Download the Excel Catalogue for Print Books](#)

Preface to the Third Edition

The warm reception to this book, *Nuclear Physics Theory and Experiment*, by renowned academicians and students since its inception (1967) has led to the publication of new editions in quick succession. The book has been recommended and considered as a standard and popular textbook on this subject at undergraduate and postgraduate levels of various universities. It is well-equipped to meet the challenging requirements of the students and teachers alike.

In this edition two important appendices— The Concept of Cross-Section for a Nuclear Reaction and the Wigner-Eckart Theorem have been included at the end of the book that will help the students in their self-study and understanding the subject in a better way.

Updates in the text have been made wherever necessary.

PUBLISHER

Contents

<i>Preface to the Third Edition</i>	(v)
<i>Preface to the First Edition</i>	(vii)
1. Introduction	1
2. Nuclear Size and Nuclear Shapes	4
2.1 Scattering Methods	4
2.2 Electromagnetic Methods	9
2.3 Nuclear Shapes	27
2.4 Electric Moments	27
2.5 Magnetic Moments	35
• <i>References</i>	39
• <i>Problems</i>	41
3. The Two-Nucleon Problem	42
3.1 Introduction	42
3.2 The Ground State of the Deuteron	45
3.3 Excited States of the Deuteron	48
3.4 Neutron-Proton Scattering at Low Energies	50
3.5 Scattering Length	53
3.6 Spin-Dependence of Neutron-Proton Scattering	54
3.7 Singlet State in n - p System	56
3.8 Effective Range Theory in n - p Scattering	57
3.9 Significance of the Sign of the Scattering Length	60
3.10 Coherent and Incoherent Scattering	61
3.11 Tensor Forces and the Deuteron Problem	66
3.12 Proton-Proton Scattering at Low Energy	74
3.13 Analysis of n - p and p - p Scattering	78
3.14 Interpretation of p - p and n - n Scattering	86
3.15 Polarization	87
3.16 Photodisintegration of the Deuteron	90
• <i>References</i>	101
• <i>Problems</i>	103

4. Phenomenology of the Two-Nucleon Interaction	105
4.1 Introduction	105
4.2 Phase-Shift Analysis	106
4.3 S-Matrix Approach	109
4.4 Experimental Scattering Parameters	112
4.5 Phase-shift Analysis of Experimental Parameters	115
4.6 Phenomenological Two-Nucleon Potential	116
4.7 Meson Theoretic Potential	126
4.8 Conclusion	129
• <i>References</i>	130
• <i>Problems</i>	132
5. Semi-Empirical Mass Formulas and Nuclear Fission	133
Part I: Semi-Empirical Mass Formulas	133
5.1 Potential Energy	135
5.2 Kinetic Energy	138
5.3 Coulomb Energy	142
5.4 Pairing Energy	142
5.5 Shell Effect	145
5.6 Atomic Masses	147
5.7 Significance of Atomic Mass	149
Part II: Nuclear Fission	151
5.8 Cross-section	151
5.9 Spontaneous Fission	153
5.10 Mass and Energy Distribution of Fragments	154
5.11 Liquid-Drop Model	156
5.12 Barrier Penetration	162
5.13 Comparison with Experiment	164
5.14 Statistical Model of Fission	165
5.15 Photofission	168
• <i>References</i>	170
• <i>Problems</i>	171
6. Nuclear Reactions I: Compound Nucleus and Statistical Model	172
6.1 Nuclear Reactions and Cross-sections	172
6.2 Resonance: Breit-Wigner Dispersion Formula for $l = 0$	176
6.3 Breit-Wigner Dispersion Formula for all Values of l	183
6.4 The Compound Nucleus	187
6.5 Continuum Theory of Cross-section σ_C	190
6.6 Statistical Theory of Nuclear Reactions	192

6.7	Evaporation Probability and Cross-sections for Specific Reactions	194
6.8	Experimental Results	196
•	<i>References</i>	209
•	<i>Problems</i>	210
7.	Nuclear Model I : Nuclear-Shell Model	212
7.1	Introduction	212
7.2	Single-Particle Potentials	213
7.3	Spin-Orbit Potential	218
7.4	Analysis of Shell Model Predictions	220
7.5	Single-Particle Model	222
7.6	Total Spin J for Various Configurations $(j)^k$	223
7.7	Nuclear Isomerism	228
7.8	Magnetic Moment	229
7.9	Configuration Mixing	231
7.10	Individual (Independent)-Particle Model	234
7.11	Russell-Saunders Coupling (L-S Coupling)	236
7.12	j - j Coupling Scheme	238
7.13	Transformation between the L-S and the j - j Coupling Schemes	239
7.14	Coefficient of Fractional Parentage (cfp)	240
7.15	Beta Decay	243
•	<i>References</i>	245
•	<i>Problems</i>	246
8.	Nuclear Model II: Unified (Collective) Model	248
8.1	Introduction	248
8.2	Nuclear Rotational Motion: Rotational Energy Spectra and the Nuclear Wave Functions for Even-Even Nuclei	249
8.3	Odd-A Nuclei: Energy Spectrum and Wave Function	252
8.4	Nuclear Moments	256
8.5	Collective Vibrational Excitations	265
8.6	Collective Oscillations: Liquid-Drop Model	265
8.7	Quadrupole Deformation	270
8.8	Nuclear Moments	272
8.9	Davydov and Filippov's Model	276
8.10	Nilsson Potential	283
8.11	Coupling between Modes of Collective Excitation	293
8.12	Rotation-Particle Coupling	295
8.13	Core Excitation	297

•	<i>References</i>	299
•	<i>Problems</i>	300
9.	Many-Body Treatment of the Nucleus	302
9.1	Introduction	302
9.2	Reaction Matrix	303
9.3	Transformation to Coordinate Space: Nuclear Matter	306
9.4	Two-Particle Wave Function	308
9.5	Partial Wave Analysis	310
9.6	Treatment of the Problem with a Hard Core in the Two-Nucleon Potential	314
9.7	Bethe-Goldstone's Treatment of the Repulsive Core	316
9.8	Theory of the Finite Nucleus	321
•	<i>References</i>	330
10.	Nuclear Reactions II: Optical Model	332
10.1	Introduction	332
10.2	Optical Model at Low Energies	334
10.3	Kapur-Peierls Dispersion Formulas for Potential Scattering	337
10.4	Dispersion Formula for the Many-Body Case	341
10.5	Lane, Thomas, and Wigner Model: Giant Resonances	345
10.6	Optical Model, Experimental	348
10.7	Conclusion	365
•	<i>References</i>	367
•	<i>Problems</i>	369
11.	Nuclear Reactions III: Direct Reactions	370
11.1	Introduction	370
11.2	Kinematics of the Stripping and Pick-up Reactions	372
11.3	Theory of the Stripping and Pick-up Reactions	375
11.4	Reverse Reaction	380
11.5	Stripping Reaction	382
11.6	Distorted-Wave Method	392
11.7	Direct Processes (Inelastic Scattering or Surface Reaction)	398
•	<i>References</i>	405
•	<i>Problems</i>	407
12.	Electromagnetic Interactions with Nuclei	408
12.1	The Multipole Expansion	408
12.2	Sources of Multipole Radiation	415
12.3	Multipole Moments	419
12.4	Angular Distribution of the Multipole Radiation	421

12.5	Parity Considerations and Selection Rules	424
12.6	γ -Decay Transition Probabilities in Nuclear Systems	424
12.7	Quantum Mechanical Derivation of the Transition Probabilities	426
12.8	The Cross-Section of $p + n \rightleftharpoons D + \gamma$	429
12.9	The Internal Conversion Phenomenon	443
12.10	Gamma-Gamma Angular Correlation	452
•	<i>References</i>	465
•	<i>Problems</i>	466
13.	Beta Decay	467
13.1	Introduction	467
13.2	Experimental Verification of the Existence of the Neutrino	468
13.3	Interaction Operators	474
13.4	Interaction Hamiltonian for Beta Decay	475
13.5	Transition Probability for Beta Decay	476
13.6	Nuclear Matrix Elements for Unpolarized Initial and Final Nucleus	478
13.7	Nuclear Matrix Elements for Beta Decay of Polarized Nuclei	480
13.8	Fermi and Gamow-Teller Selection Rules for Allowed Beta Decay	481
13.9	Matrix Elements between Lepton States for Unpolarized Electron and Neutrino	483
13.10	Polarization of Electrons in Beta Emission	490
13.11	Beta Decay from Oriented (Polarized) Nuclei	493
13.12	General Expressions	498
13.13	Two-Component Theory of the Neutrino	502
13.14	Conservation of Leptons	505
13.15	Conservation of Vector Current (CVC) Theory	506
•	<i>References</i>	507
•	<i>Problems</i>	509
	Appendix A	511
	Mathematical Preliminaries	511
A.1	Expressions for ∇ , ∇^2 , and $\mathbf{l} = \mathbf{r} \times \mathbf{p}$ in Different Coordinate Systems	511
A.2	Spherical Harmonics	513
A.3	Three-Dimensional Square-Well Potential	515
A.4	Plane-Wave Expansion in Spherical Harmonics	518
A.5	Spherical Harmonics: Transformation Properties under Rotation	518

A.6	Properties of the D -Matrices	520
A.7	Addition of Two Angular Momenta	522
A.8	Explicit Expressions for the Clebsch-Gordan Coefficients	524
A.9	Coupling of Three Angular Momenta	526
A.10	Further Discussion of the Rotation Matrix D	528
A.11	The Wigner-Eckart Theorem	530
A.12	Scattering of a Particle by a Central Potential	533
A.13	The Scattering Matrix: S -Matrix	536
A.14	Scattering by a Coulomb Field	538
A.15	Scattering by Combined Nuclear and Coulomb Potentials	541
A.16	Tensor Operator	542
A.17	Scattering Phase-Shift Analysis with Tensor Forces	545
A.18	Isotopic Spin of the Nucleon	551
A.19	Two-Nucleon Wave Function in Isospin Space	552
A.20	Complete Wave Function for the Two-Nucleon System: Pauli Principle	553
A.21	Dirac Equation	555
Appendix B:		561
The Concept of Cross-Section for a Nuclear Reaction		561
Appendix C:		564
The Wigner-Eckart Theorem		564
Author Index		569
Subject Index		579

Introduction

CHAPTER

1

The atomic nucleus was discovered in 1911 by Rutherford, who demonstrated that the large-angle alpha-particle scattering can be explained only in terms of a positively charged nucleus of radius $\sim 10^{-12}$ cm as compared to a radius $\sim 10^{-8}$ cm for the atom. In addition, the nucleus is massive and contains practically the whole of the mass of the atom.

Before Rutherford, however, there were many other outstanding developments. In 1896, Becquerel identified radioactivity, and the following year J. J. Thomson discovered the electron. A year later, Marie Curie isolated polonium and radium from the ores. The theory of radioactivity was systematized shortly after by the statistical decay law due to Rutherford, Soddy, and Von Schweidler. It was also found that the radiations emitted from radioactive substances could be classified as alpha-, beta-, and gamma-rays by observing the deflection of alpha- and beta-rays in a magnetic field.

Roentgen discovered x-rays in 1895, and Von Laue in 1912 observed their diffraction. From Moseley's study of x-ray spectra in 1913 emerged the concept of atomic number Z which became the basis for the classification of elements in the periodic table. Bohr, in the same year, explained the hydrogen spectrum by assuming a simple model of the atom which incorporated both the atomic number Z and the quantum of radiation first proposed by Planck in 1900. The discovery of the Rutherford-Bohr model of the atom was followed by the advent of quantum mechanics which explained, in great detail, various atomic phenomena. Quantum mechanics as a tool to understand atomic phenomena; it was developed by numerous physicists, among whom are de Broglie, Schrödinger, Heisenberg, Pauli, and Dirac.

Rutherford, in 1919, was the first to demonstrate the phenomenon of nuclear reaction by the disintegration of nitrogen according to the reaction ${}_7\text{N}^{14} + {}_2\text{He}^4 \rightarrow {}_8\text{O}^{17} + {}_1\text{H}^1$. The concept of the structure of the nucleus remained unexplained until 1932 when a neutral particle, the neutron, was discovered by Chadwick, following a series of experiments by Bothe, Joliot, and Chadwick. After this important discovery, it was proposed that the nucleus was composed of neutrons and protons which have almost the same mass. The mass number A of the nucleus is given by the sum of Z protons and $A-Z$ neutrons. This concept of the nucleus which arose in the 1930s is still valid today. Neutrons and protons, commonly referred to as nucleons, are spin-half particles, which obey Fermi-Dirac statistics.

The basic problem in nuclear physics is determining the nature of the force which holds the neutral particles, such as neutrons, and the charged particles, such as protons. The force, of course, cannot be electrical in origin since a neutron carries no charge. The interpretation of the scattering experiments indicated that this force must be of short range extending to a distance less than 10^{-11} cm. Yukawa, in 1935, introduced the concept of mesonic force in nuclear interaction. In 1936, Anderson and Neddermeyer discovered μ -meson which was followed by the discovery by Powell in 1946 of still another heavier meson, π -meson. Since then numerous new particles have been discovered. The situation may seem somewhat confusing. However, although the exact nature of the nucleus is still a mystery, much progress has been made towards its understanding.

We shall briefly summarize the various topics presented in this book. We have limited ourselves for the most part to the discussion of low energy phenomena; in Chapter 4, however, we have reviewed the nucleon-nucleon interaction phenomenologically over an energy range extending to about 300 Mev.

Extensive mathematical development is required in understanding and interpreting the problems in nuclear physics. In fact, mathematics has become an integral part of the subject. To emphasize this point, we have included in the Appendix the mathematical formalisms that are essential for developing the various topics throughout the book.

Chapter 2 deals with the nuclear radius and nuclear shapes. Various methods for determining the nuclear radius are examined with special emphasis on the more accurate and recent methods, such as electron scattering. We note particularly that the values obtained in the determination of the nuclear radius are dependent upon the method used. If the nuclear radius found by the alpha scattering method does not agree with that found by the electron scattering, it is because alpha scattering determines the interaction radius, whereas electron scattering gives the density of charge distribution of the nucleus. The structure of a nucleus is explained by the interaction of the nuclear electric charge and magnetic moment distributions with either the external or internal (atomic electrons) electromagnetic field. The electric quadrupole moment measures the deviation of charge distribution from a spherical shape. On the other hand, the magnetic moment of a nucleus interacts with the magnetic field in which the nucleus is located. General expressions for electric and magnetic multipoles are given.

Nuclear forces are complex and are difficult to understand. Of course, the two-nucleon interaction is comparatively simpler and easier to understand than many-nucleon forces. Chapter 3 covers the two-nucleon interaction in considerable detail by treating its different aspects.

The nuclear mass and the nuclear fission are described by semi-empirical formulas (Chapter 5) which are, in part, related to the liquid drop model of the nucleus. Although many-nucleon forces are not understood completely, the semi-empirical approach in solving these problems helps a great deal in understanding the nuclear mass and the mechanism of nuclear fission.

Nuclear reactions have been studied extensively, both experimentally as well as theoretically. Experimentally, data can be collected with great accuracy by using precise techniques. These data are often analysed in terms of theoretical models such as the compound nucleus, statistical model (Chapter 6), optical model (Chapter 10), direct reaction mechanism (Chapter 11), etc. Such analyses are helpful in understanding the mechanism of nuclear reactions. Theoretical calculations underlying each of these models together with the experimental results are presented.

Considerable progress in the study of nuclear structure has been made by the development of the nuclear shell-model. This model, although basically simple, has led to the explanation of many nuclear properties such as spin, magnetic moment, and nuclear spectra. This model is discussed in Chapter 7.

There are many properties of nuclei, such as large electric quadrupole moments, deviations from the spherical shape, and rotational and vibrational spectra, which cannot be understood in terms of the nuclear shell-model. These properties are a consequence of the collective motion of many nucleons. In Chapter 8 we explore the collective model and its several variations.

The theory of the nuclear many-body problem, basing it on the two body interaction, is given in Chapter 9. By thus reducing the complex problem into a more workable form, theories make an attempt to describe the properties of nuclear matter.

The study of electromagnetic interaction with nuclei provides much information concerning the nuclear properties. The processes which can be treated are emission of γ -rays, conversion electrons from excited nuclei, γ - γ angular correlations, emission of nucleons with the absorption of photon, and others. Chapter 12 gives a comprehensive discussion of these processes. Experimental data have also been compared with the predictions made by the theory.

Until 1956, Fermi's theory was adequate to explain various aspects of the beta decay process. However, in 1956 its concept was revised to a great extent when Lee and Yang discovered that in weak interaction processes parity is not conserved. Even after this discovery, however, Fermi's theory was not found to be redundant. Chapter 13 describes the beta decay process, emphasizing this modified theory.

NUCLEAR PHYSICS

THEORY AND EXPERIMENT

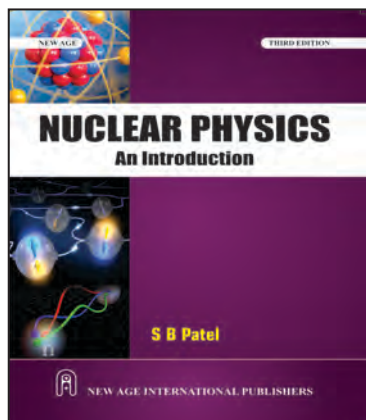
This book is presented as a two semester undergraduate-level course. Most of its contents can be understood by students who have had one year of quantum mechanics. Some chapters may also be useful to advanced undergraduate students. Certain parts can also serve as reference material. In this new edition of the book two appendices have been added to update the information on Cross-Section for a Nuclear Reaction and another on Wigner-Eckart Theorem.

Some of the salient features:

- Various methods for determining the nuclear radius are examined with special emphasis on the more accurate and recent methods, such as electron scattering.
- General expressions for electric and magnetic multipoles are given.
- The nuclear mass and nuclear fission are described by semi-empirical formulas.
- The two-nuclear interaction in considerable detail by treating its different aspects and the nuclear shell-model are discussed in detail.
- Certain standard mathematical expressions, with their derivations, appear in the Appendix.

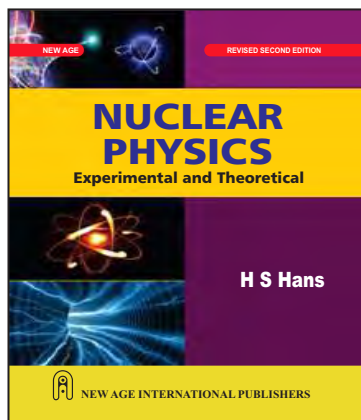
Readership: Undergraduate students and Faculty of Physics • University and college libraries
• Researchers and professionals.

Our Other Related Titles



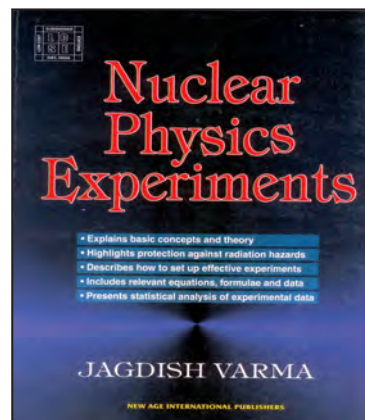
ISBN: 978-81-224-7241-7
PB Pgs: 386 MRP: ₹399.00

[Click Here to Buy the Book Online](#)



ISBN: 978-81-224-3141-4
PB Pgs: 784 MRP: ₹499.00

[Click Here to Buy the Book Online](#)



ISBN: 978-81-224-1298-7
PB Pgs: 202 MRP: ₹42.00

[Click Here to Buy the Book Online](#)

Committed to Educate the Nation



Publishing Globally

IN INDIA

NEW AGE INTERNATIONAL (P) LIMITED, PUBLISHERS

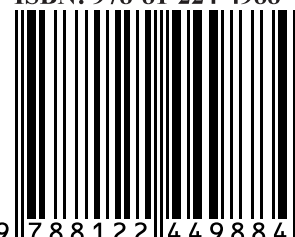
LONDON • NEW DELHI

Bangalore • Chennai • Cochin • Guwahati • Hyderabad • Kolkata • Mumbai

Visit us at www.newagepublishers.com

MRP: ₹ 499.00

ISBN: 978-81-224-4988-4



9 788122 449884

Available at Your Nearest Booksellers